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Analysis of Earthquake Data from the Greater Los Angeles Basin and Adjacent Offshore Area, Southern California

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ABSTRACT

We synthesize and interpret local earthquake data recorded by the Caltech/USGS Southern California Seismographic Network (SCSN/CISN) in southern California. The goal is to use the existing regional seismic network data to: (1) refine the regional tectonic framework; (2) investigate the nature and configuration of active surficial and concealed faults; (3) determine spatial and temporal characteristics of regional seismicity; (4) determine the 3D seismic properties of the crust; and (5) delineate potential seismic source zones. Because of the large volume of data and tectonic and geologic complexity of the area, this project is a multi-year effort and has been divided into several tasks.

RESULTS

The 2015 Fillmore Earthquake Swarm and Possible Crustal Deformation Mechanisms near the Bottom of the eastern Ventura Basin, California

The 2015 Fillmore swarm occurred about 6 km west of the City of Fillmore in Ventura, California, and was located beneath the eastern part of the actively subsiding Ventura basin at depths from 11.8 km to 13.8 km, similar to two previous swarms in the area (Figure 1). Template-matching event detection showed that it started on the 5th of July 2015 at 2:21 UTC with a ~M1.0 earthquake. The swarm exhibited unusual episodic spatial and temporal migrations, and diversity in nodal planes of focal mechanisms as compared to the simple hypocenter defined plane. It was also noteworthy because it consisted of >1,400 events of $M \geq 0.0$, with M2.8 being the largest event. We suggest that fluids released by metamorphic dehydration processes, migration of fluids along a detachment zone, and cascading asperity failures caused this prolific earthquake swarm, but other mechanisms such as simple mainshock-aftershock stress triggering or a regional aseismic creep event are less likely. Dilatant strengthening may be a mechanism that causes the temporal decay of the swarm as pore pressure drop increased the effective normal stress, and counteracted the instability driving the swarm.

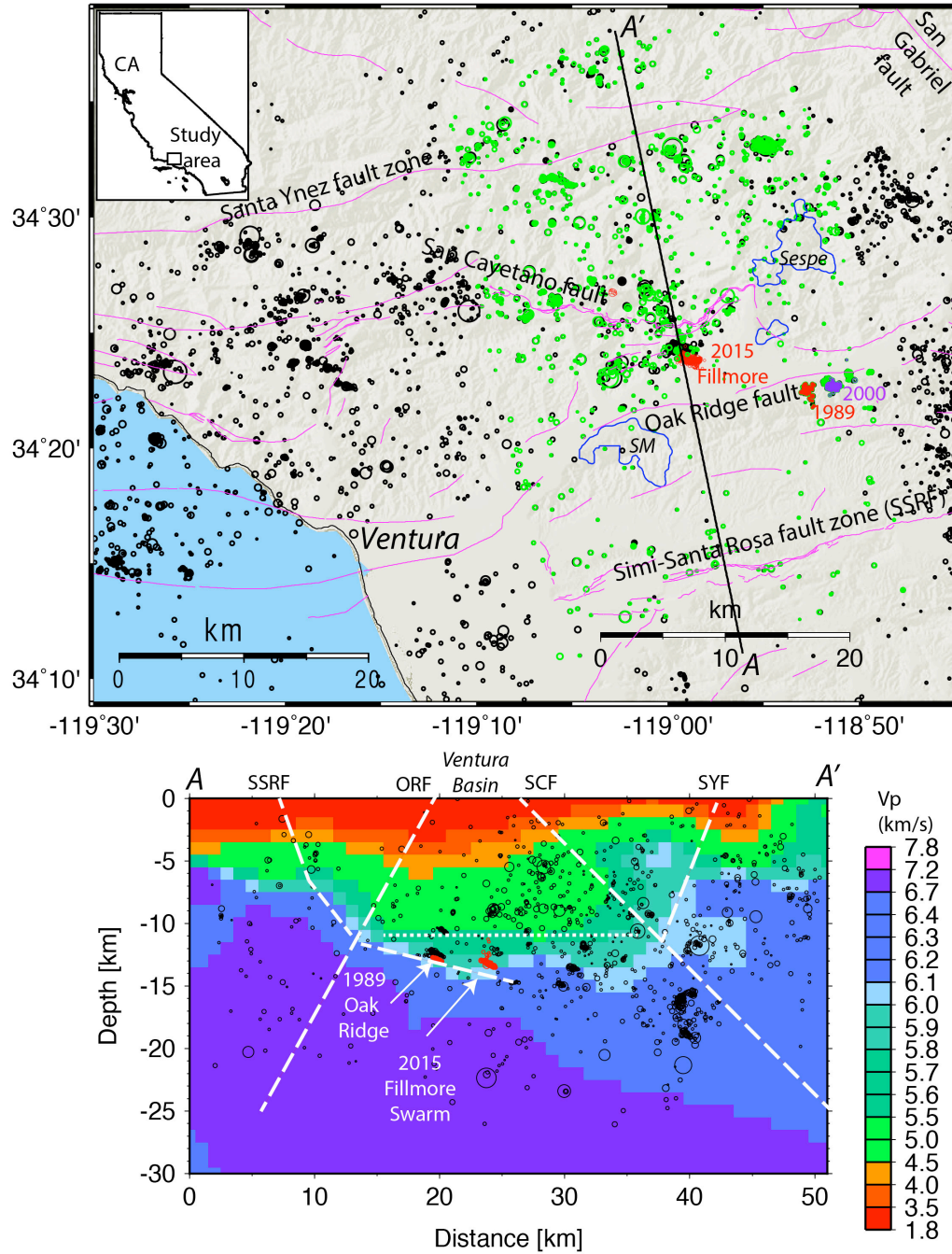


Figure 1. Map and cross section view of regional seismicity, with events in the cross-section plotted in green on the map. Outlines for three oilfields (South Mountain (SM), Sespe, and Fillmore) are shown. The cross section shows modified 3D V_p model from Shaw et al. (2015), and approximate locations of late Quaternary faults in the cross section from the Southern California Earthquake Center/Community Fault Model (SCEC/CFM) (Plesch et al., 2007; Marshall et al., 2013; and Nicholson et al., 2014). The 1989 and 2015 swarms are plotted in red color, and the 2000 swarm in purple in map view. Location of study area within California is shown in upper left corner as a rectangle.

The Fillmore swarm expanded mostly down-dip from east to west in map view, but low level of activity continued through the duration of the swarm near its origin. The N12°W trending cross-section shows a dipping zone of seismicity no wider than 50 m extending across an area of approximately 1 km by 1.5 km, in the depth range of 11.8 to 13.8 km. The swarm defines a remarkably planar zone dipping 26° to N12°W. There is also some indication of a second less active plane about ~100 m above the main plane of hypocenters.

The 2015 Fillmore swarm activity peaked on 9th and 10th of July with the largest event of M2.8, and continued with several smaller spurts of activity, and tapered off in late July to late September. The overall spatial and temporal evolution of the sequence consisted of two distinct episodes of westerly down-dip migration of the swarm events. The main cluster is shown in light blue to green while the late cluster is shown in red. In cross-section view the 5-10 July burst occurred across most of the activated zone. On July 13-14 the west down-dip edge was activated. From the end of July until late September the activity had resumed again at the initiation point, becoming increasingly more scattered towards the end of the sequence. In comparison, the 1989 swarm that consisted of 50 events, with the largest event of M2.2, was located ~8 km to the south-southwest near Oak Ridge (Shearer, 1998). Its spatial-temporal migration was different, with the 1989 swarm outlining a more circular zone of deformation (Shearer, 1998).

The detailed evolution of the Fillmore swarm with time, distance from first event, and focal depth shows the two main spurts of activity superimposed on a steady background rate near the origin of the swarm. The swarm had a low level onset lasting for ~4 days. The major spurt of activity occurred around the 9th and 10th of July. The 2nd spurt occurred around the 14th of July. Several small spurts continued near the point of initiation to late September. Assuming a stress drop of 3 MPa the rupture lengths for the largest events are on the order of 200 to 300 m. The diffusivity curves fit to the whole swarm suggest an overall rate of diffusivity of 0.2 to 0.3 m²/s when assuming a one-dimensional model (Malagnini et al., 2012). The rate of event migration is significantly higher for the two main clusters (~0.06 km/hr) as compared with a rate of 0.003 km/hr for the whole sequence, showing that at least two different time constants seem to be required to match the time-space evolution. The best-fit overall diffusivity fit curves indicate that the swarm migration was consistent with plausible fluid movement rates, while the occurrence of the two clusters suggested cascading asperity failures and complex feedback with deformation in the area where the swarm originated (*for further details see, Hauksson et al. 2016*).

Detecting earthquake stress drop variations: A comparison between a convergent step-over in the San Andreas Fault and the Ventura thrust fault system, southern California

A key parameter in engineering seismology and earthquake physics is seismic stress drop, which describes the relative amount of high-frequency energy radiation at the source. To identify regions with potentially significant stress drop variations, we perform a comparative analysis of source parameters in the greater San Geronimo pass (SGP) and Ventura basin (VB) in southern California (Figure 1). The identification of physical stress drop variations is complicated by large data scatter as a result of attenuation, limited recording bandwidth and imprecise modeling assumptions. In light of the inherently high uncertainties in single stress drop measurements, we follow the strategy of stacking large numbers of source spectra thereby enhancing the resolution of our method. We analyze more than 6000 high-quality waveforms between 2001 and 2014, and compute seismic moments, corner frequencies and stress drops.

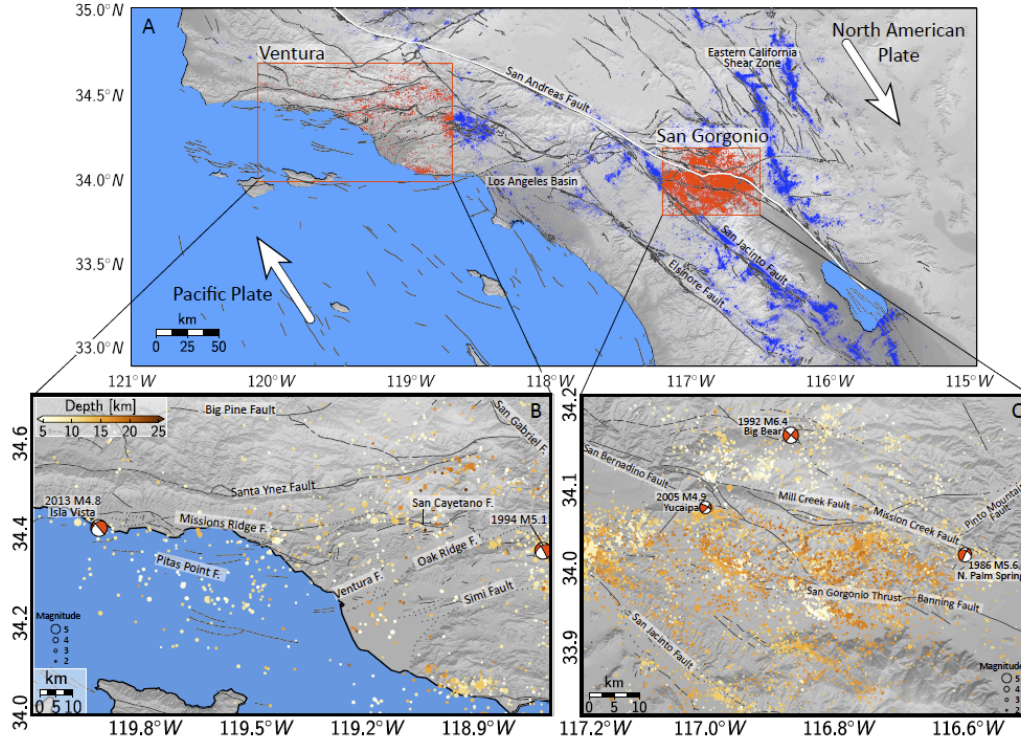


Figure 1: Seismicity and major faults in southern California (A). Study regions (SGP: [117.2W, 33.8N] to [116.5W, 34.2N] and VB [120.1W, 34.0N] to [118.7W, 34.7N]) and corresponding seismicity are highlighted in red, white arrow show approximate direction of relative plate motion. Seismicity colored with depth and scaled with magnitude in the greater VB (B) and SGP(C) regions. Fault traces are highlighted by black lines.

Significant variations in stress drop estimates exist within the SGP area. Moreover, the SGP also exhibits systematically higher stress drops than VB and shows more scatter. We demonstrate that the higher scatter in SGP is not a generic artifact of our method but an expression of underlying differences in source processes. Our results suggest that higher ambient stresses, which can be deduced from larger focal depth and more thrust faulting, may only be of secondary importance for stress drop variations. Instead, the general degree of stress field heterogeneity and strain localization may influence stress drops more strongly, so that more localized faulting and homogeneous stress fields favor lower stress drops. In addition, higher regional loading rates, for example, across the VB potentially result in stress drop reduction whereas localized slow loading rates on structures within the SGP result in anomalously high stress drop estimates. Our results show that crustal and fault properties systematically influence earthquake stress drops of small and large events and should be considered for seismic hazard assessment.

The comparative analysis of stress drop variations in VB and SGP showed that stress drop estimates of individual earthquakes can vary strongly over up to three orders of magnitude. This scatter may not solely be due to measurement uncertainty but rather indicate real-variations in stress drop estimates. To confirm these results, we test whether statistical significant stress drop variations are resolvable in large (>100s earthquake) sample sizes. First, we smoothed spatial representations of stress drop estimates and binned depth variations. Second, we examine the robustness of stress drop variations by analyzing corner frequency and seismic moment estimates as well as spectral shapes of stacked source terms (for further details, see: Goebel *et al.* 2016).

References

- Goebel, T. H. W., E. Hauksson, A. Plesch, and J. Shaw, Detecting significant stress drop variations in large micro-earthquakes datasets: A comparison between a convergent step-over in the San Andreas Fault and the Ventura thrust fault system, southern California; Special Volume of *Pure and Applied Geophysics*; p1420-9136, DOI: 10.1007/s00024-016-1326-8, 2016.
- Hauksson, E., J. Andrews, A. Plesch, J. H. Shaw, and D. R. Shelly, The 2015 Earthquake Swarm Near Fillmore, California: Possible Dehydration Event Near the Bottom of the Over-Pressurized Ventura Basin, in press, *Seismological, Res. Letters*, v87, nr4, p807-815, doi: 10.1785/0220160020, 2016
- Malagnini, L., F. P. Lucente, P. De Gori, A. Akinci, and I. Munafo' (2012), Control of pore fluid pressure diffusion on fault failure mode: Insights from the 2009 L'Aquila seismic sequence, *J. Geophys. Res.*, 117, B05302, doi:10.1029/2011JB008911.
- Shearer, M., P., Evidence from a cluster of small earthquakes for a fault at 18 km depth beneath Oak Ridge, southern California (1998), *Bull. Seismol. Soc. Am.*, **88**, 1327–1336.

Recent refereed publications

- Goebel, T. H. W., S.M. Hosseini, F. Cappa, E. Hauksson, J.-P. Ampuero, F. Aminzadeh and J.B. Saleeby. "Wastewater disposal and earthquake swarm activity at the southern end of the Central Valley, California", *Geophys. Res. Letts*, 43, 1-8, doi:10.1002/2015GL066948.
- Hauksson, E., J. Andrews, A. Plesch, J. H. Shaw, and D. R. Shelly, The 2015 Earthquake Swarm Near Fillmore, California: Possible Dehydration Event Near the Bottom of the Over-Pressurized Ventura Basin, in press, *Seismological, Res. Letters*, v87,nr4, p807-815, doi: 10.1785/0220160020, 2016
- Goebel, T. H. W., E. Hauksson, A. Plesch, and J. Shaw, Detecting significant stress drop variations in large micro-earthquakes datasets: A comparison between a convergent step-over in the San Andreas Fault and the Ventura thrust fault system, southern California; Special Volume of *Pure and Applied Geophysics*; p1420-9136, DOI: 10.1007/s00024-016-1326-8, 2016.
- Castro, R. R., J. Stock, E. Hauksson, and R. Clayton, Source Functions and Path Effects from Earthquakes in the Farallon Transform Fault Region, Gulf of California, Mexico that Occurred on October 2013; Special Volume of *Pure and Applied Geophysics*; p 1420-9136, DOI: 0.1007/s00024-016-1346-4; 2016
- Goebel, T. H. W., E. Hauksson, F. Aminzadeh, and J.-P. Ampuero (2015), An objective method for the assessment of possibly fluid-injection induced seismicity in tectonically active regions in central California, *J. Geophys. Res.*, 120, 1-20, doi:10.1002/2015JB011895.
- Goebel, T. H. W., E. Hauksson, P. M. Shearer, and J. P. Ampuero, Stress-drop heterogeneity within tectonically complex regions: A case study of the San Geronio Pass, southern California, *Geophys. J. Int.* (2015) 202, 514–528 doi: 10.1093/gji/ggv160
- Hauksson, E., T. Goebel, and J.-P. Ampuero, Cochran, E. (2015), A century of oilfield operations and earthquakes in the greater Los Angeles basin, southern California, *The Leading Edge (SEG), Special Volume: Injection-induced seismicity*, eds. Robert Habiger, Gregory Beroza 34(6), 650-656, <http://dx.doi.org/10.1190/tle34060650.1>.
- Shaw, J. H., A. Plesch, C. Tape, M. P. Suess, T. Jordan, G. Ely, E. Hauksson, J. Tromp, T. Tanimoto, R. Graves, K. Olsen, C. Nicholson, P. Maechling, C. Rivero, P. Lovely, C. M. Brankman, and J. Munster, Unified Structural Representation of the southern California crust

and upper mantle, *Earth and Planetary Science Letters*, [dx.doi.org/10.1016/j.epsl.2015.01.016](https://doi.org/10.1016/j.epsl.2015.01.016), 2015.

Abstracts for recent oral, reports, or poster presentations

Hauksson, E., Regional tectonic stress field and earthquake stress drops in southern California: Understanding distributed continental plate boundary tectonics; (Abstract) presented at the *2016 Seismological Soc. America meeting in Reno, NV, 17 April 2016*

Goebel, T. H. W., Hosseini, S. M., Cappa, F., Hauksson, E., Ampuero, J. P., Aminzadeh, F., Saleeby, J. B., Wastewater Disposal and Earthquake Swarm Activity at the Southern End of the Central Valley, California. (Abstract) to be presented at the *2016 Seismological Soc. America meeting in Reno, NV, 17 April 2016*

Goebel, T. H. W., Hauksson, E., Plesch, A., Shaw, J. H., Seismicity Statistics and Stress in Regions with High Tectonic Complexity: A Comparative Study of the Greater San Geronio and Ventura Regions in Southern California. (Abstract) presented at the *2016 Seismological Soc. America meeting in Reno, NV, 17 April 2016*

Castro, R. R., J. Stock, E. Hauksson, R. Clayton, Source Functions and Path Effects from Earthquakes in the Farallon Transform Fault Region, Gulf of California, Mexico that occurred on October 2013; (Abstract) presented at the *2016 Seismological Soc. America meeting in Reno, NV, 17 April 2016*

Castro, R. R., R. Clayton, E. Hauksson, and J. Stock, Observations of Remotely Triggered Seismicity in Salton Sea and Coso Regions, Southern California, After Big ($M_w > 7.8$) Recent Earthquakes; (Abstract), to be Presented at *2016 IASPEI Costa Rica*.

Castro, R., R. Clayton, E. Hauksson, J. Stock, Disparo Remoto de Sismicidad en Las Regiones de Los Campos Geotermicos del Salton Sea y Coso, Sur de California, despues de telesismos grandes ($M_w > 7.8$); (Abstract), Union Geofisica Mexicana (UGM) meeting, fall 2016.

Hauksson, E., T. H. W. Goebel, J. P. Ampuero, and E. Cochran, Oilfield operations and earthquakes in the greater Los Angeles basin, southern California: analyzing a century of data, including volume changes and M_{max} (Abstract) *Seismological Research Letters*, **V86**, 2, March/April 2015.

Nicholson, C., A. Plesch, C. Sorlien, J. H. Shaw, and E. Hauksson. The SCEC Community Fault Model Version 5.0: An updated and expanded 3D fault set for southern California, Abstract; presented at the 2015 Pacific Section AAPG meeting, Oxnard, CA.

Donnellan, A., J. W. Parker, L. Grant Ludwig, J. B. Rundle, E. Hauksson, UAVSAR observation of active structures associated with the 2014 m 5.1 La Habra earthquake (Abstract) *Seismological Research Letters*, **V86**, 2, March/April 2015.

Goebel, T. H. W., E. Hauksson, A. Plesch, and J. Shaw, Seismicity statistics and stress in regions with high tectonic complexity: a comparative study of the greater San Geronio and Ventura regions in southern California (Abstract) *Seismological Research Letters*, **V86**, 2, March/April 2015.

Goebel, T. H. W., E. Hauksson, A. Plesch, and J. H. Shaw, Seismicity statistics and stress in regions with high tectonic complexity: A comparative study of the greater San Geronio and Ventura regions in southern California; *Talk presented at: APEC Cooperation for Earthquake*

Simulation, 9th ACES Symposium on Earthquakes and Multihazards Chengdu, China, August 10–16, 2015.

Hauksson, E., A century of oilfield operations and earthquakes in the greater Los Angeles basin, southern California; Abstract; presented at: California Well Stimulation (CWS) Forum, USC, Los Angeles, CA; 24 July 2015.

Nicholson, C., A. Plesch, C.C. Sorlien, J. H. Shaw, and E. Hauksson (2015, 05), The SCEC Community Fault Model Version 5.0: An updated and expanded 3D fault set for southern California, Poster Presentation at 2015 Pacific Section AAPG Joint Annual Meeting.

Hauksson, E., J. Andrews, J. H. Shaw, A. Plesch, D. Shelly, and C. Nicholson, The 2015 Earthquake Swarm Near Fillmore, California: Evidence for a Dehydration Event Near the Bottom of the Over-Pressurized Ventura Basin (2015 SCEC Annual Meeting Poster 167).

Shaw, J. H., M. Barall, R. Burgette, J. F. Dolan, E. L. Geist, J. Grenader, T. Gobel, W. Hammond, E. Hauksson, J. A. Hubbard, K. Johnson, Y. Levy, L. McAuliffe, S. Marshall, C. Nicholson, D. Oglesby, A. Plesch, L. Reynolds, T. Rockwell, K. J. Ryan, A. Simms, C. C. Sorlien, C. Tape, H. Thio, S. Ward, The Ventura Special Fault Study Area: Assessing the potential for large, multi-segment thrust fault earthquakes and their hazard implications (2015 SCEC Annual Meeting; talk by J. Shaw).

Hauksson, E., Exploring the brittle-ductile transition at the base of the seismogenic zone of the crust in southern California: Implications for crustal rheology, Abstract **T51H-04**; presented at 2015 Fall Meeting, AGU, San Francisco, Calif., 18 Dec.